Shoaling Wave Energy Dissipation in Turbulent Bottom Boundary Layers

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LONG-TERM GOAL

The long-term goal is to increase the understanding and predictive capability for effects of turbulent bottom boundary layers on shoaling wave fields.

OBJECTIVES

Shoaling surface waves can create turbulent boundary layers at the sea floor that make significant contributions to wave energetics, dissipation rates, and fluid-sediment interactions. The objective is to make direct estimates of wave energy dissipation rates in the bottom boundary layer and to develop predictive capabilities for these effects as a function of important environmental parameters, such as wave heights, frequency spectra, local water depth, bottom roughness (including sand ripples), and mean current conditions. The three-dimensional numerical simulations are also used to evaluate the performance of one-dimensional eddy viscosity models for the bottom boundary layer.

APPROACH

The work involves theoretical analysis, numerical computations, and comparison with field and laboratory results. The primary experimental tools are three-dimensional direct numerical simulations (DNS) (*e.g.*, Slinn and Riley, 1998) and large eddy simulations (LES) (*e.g.*, Winters *et al*., 2000) of the wave bottom boundary layer that resolve the relevant scales of motion in the shear layer at the sea-bed.

WORK COMPLETED

We have completed a study focusing on oscillatory flows over a smooth bottom surface including mean currents of varying strength in the direction normal to the wave oscillations. Ongoing work implements a new bottom boundary layer model, developed in collaboration with Kraig Winters (University of Washington), for LES and DNS simulations of flow over small scale topographic variability (*e.g.*, sand ripples). The more mature of these models and associated users guides are available on the Web at http://www.oe.fau.edu/faculty/slinn/Waves/Dissipation.html.

RESULTS

A variety of wave forcing conditions and the corresponding horizontally averaged turbulent kinetic energy (TKE) in the boundary layer over a smooth surface, as a function of height, z, and time, t, are shown in Figure 1. In general, a quasi-steady flow response to periodic wave forcing is achieved after two or three flow reversals. Turbulent bursts become episodic in nature, occurring approximately twice per wave period. Turbulence typically initiates near the wall during phases of flow deceleration, achieves its maximum intensity and vertical excursion just after flow reversal and decays rapidly as the flow accelerates in the opposite direction (Piomelli *et al*., 2000 and Gad-El-Hak *et al*., 1984). The decay of turbulence is more sudden than the onset and significant TKE extends to heights of approximately 2-4 cm depending on the forcing conditions.

The magnitude of the free-stream acceleration and deceleration are important parameters in controlling the turbulence levels in the boundary layer. When the acceleration is strong, turbulent production is inhibited. The experiment with wave packet forcing (e) shows a similar temporal response in the boundary layer TKE. Clearly, different wave-forms cause different turbulent responses in the boundary layer. Including a mean current to the wave bottom boundary layer, normal to the direction of wave oscillation, can also change the flow behavior significantly. A case with a combined wave and mean current, with $U_m = 0.6$ m s^{-1} and V_0=0.6 m s^{-1} is shown in Figure 1f and produces much higher turbulent levels than purely oscillatory flow for similar Reynolds number.

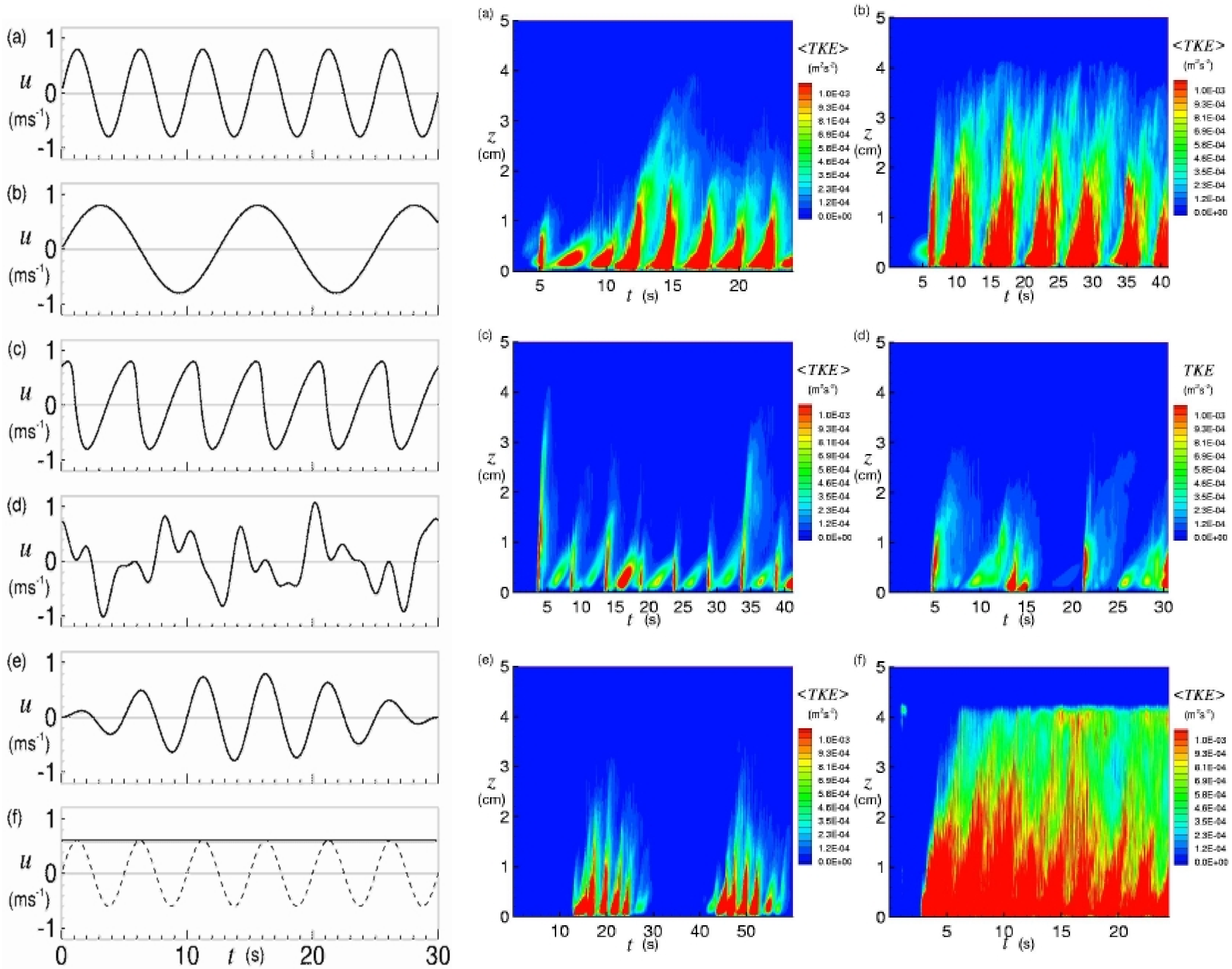

Figure 1: Free-stream forcing time series (left panel) and horizontally averaged turbulent kinetic energy as a function of time and distance from the bottom boundary for flow over a smooth bottom boundary (a) sine wave, T=5 s; (b) sine wave, T=12.5 s; (c) skewed wave; (d) complex frequency wave; (e) wave packet; (f) wave-current flow, T=5 s, and V_∞=0.6 m/s.

Quantitative comparisons of volume averaged properties between additional numerical experiments show that the mean turbulent kinetic energy increases as the period T increases, consistent with the increase in boundary layer thickness with T. The dissipation rate decreases as T increases for laminar flow but increases above the laminar results for the more turbulent cases. The mean turbulent kinetic energy and the dissipation rate also increases as the Reynolds number increases, for fixed wave period. Generally, as the mean current V_0 increases, TKE and dissipation rates also increase.

We have also examined the performance of one-dimensional wave bottom boundary layer models such as those introduced by Grant and Madsen (1979) and Trowbridge and Madsen (1984) that are based on a variable turbulent eddy viscosity. The one-dimensional model's performance is a function of wave phase and distance from the boundary. The rms difference between the one-dimensional models (G&M, T&M, and laminar) and the results of the three-dimensional simulations indicate that generally the Madsen type models closely approximate the velocity profiles determined with the 3-D model. The 1-D models have best performance for more strongly turbulent flows and complex wave forcing conditions, and poorer performance for flows with intermittent turbulence. They generally somewhat over predict the boundary layer thickness and under predict the shear stress at the sea-bed.

A new computational model has been adapted (from Winters *et al.*, 2000) to solve the three-dimensional Navier–Stokes equations for an incompressible, constant density, flow in a terrain–following coordinate system (σ–coordinates). We examine a small, horizontally periodic domain representative of oscillatory flow over sinusoidal topography using DNS and LES. The WBBL over a "sand" ripple is significantly more turbulent throughout the full flow period than over a flat bottom.

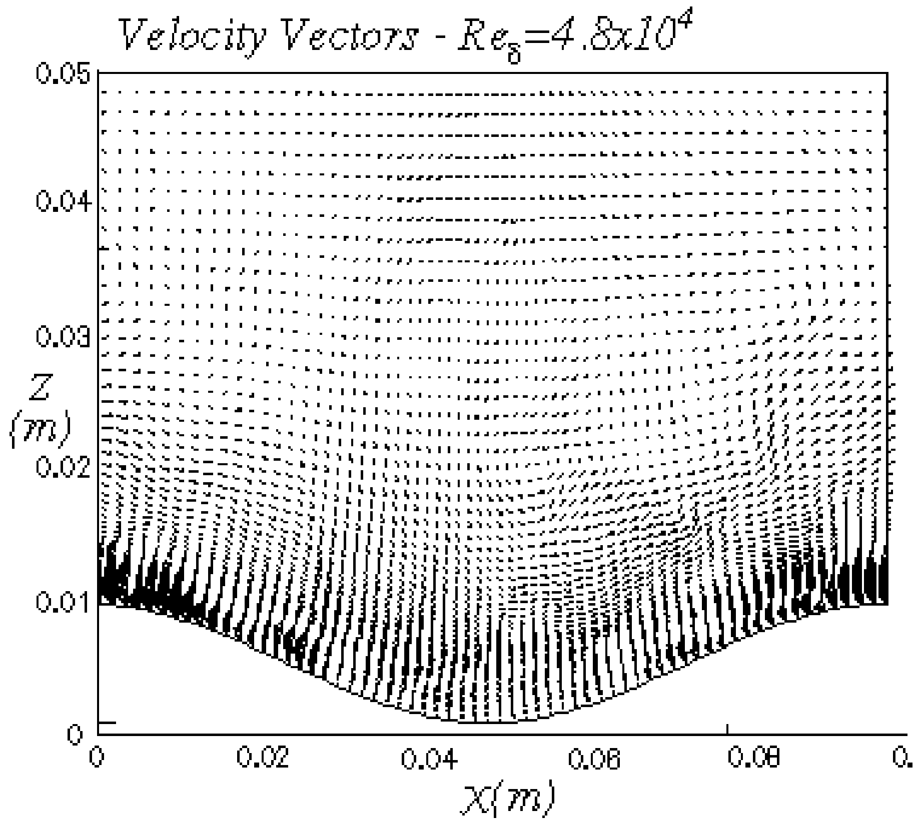

Figure 2: Velocity vectors in a 2-D plane (from a 3-D simulation) of oscillatory flow over a sinusoidal sand ripple during a phase near flow reversal.

Flow over variable topography is illustrated in Figures 2 and 3. Figure 2 depicts velocity vectors during a phase of flow reversal over a sinusoidal sand ripple with amplitude of 1 cm and wavelength of 10 cm (aspect ratios are not to scale). The boundary layer thickness increases and the duration of turbulent bursts is longer. Flow separation occurs in the lee of the ripple crests during phases of strong onshore or offshore flow. Figure 3 illustrates flow over a "peaked" sand ripple. Here the bottom topography is chosen to match natural conditions that develop in the field, that is, the ripple dimensions are set by the near bed wave-orbital excursion length.

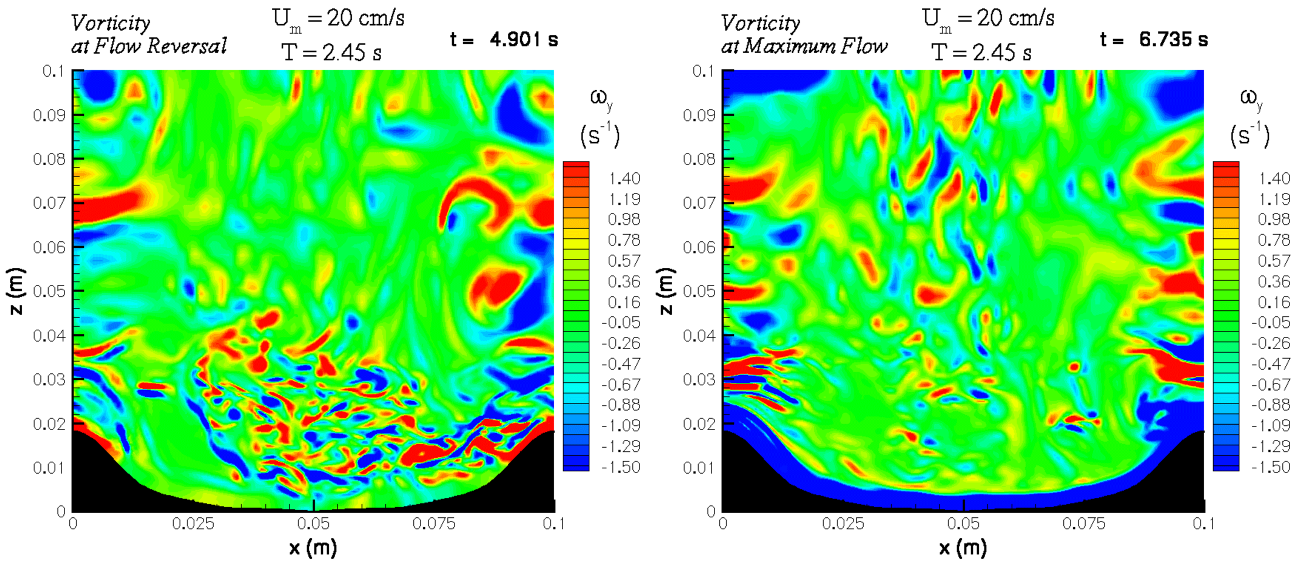

Figure 3: Vorticity fields in a 2-D plane (from a 3-D simulation) of oscillatory flow over a sharp crested sand ripple at two phases of flow, near flow reversal (left panel) and near a phase of maximum flow (right panel).

Figure 3 shows vorticity fields in a vertical cross section during two phases of flow over the ripple. Turbulent bursts still occur most strongly at phases of flow reversal. The bursts originating during flow reversal, however, are not damped out during flow acceleration, but remain strong throughout the wave period. Thus, the shoaling wave energy dissipation rates are enhanced in boundary layers over ripples compared to flows over smooth topography. A complex flow develops even for the simplest wave field forcing conditions. The shear stress on the boundary is highly variable temporally and spatially with the strongest shears occurring on the front and crests of the ripple.

IMPACT/APPLICATION

Small-scale boundary layer processes at the sea bed in shallow water are strongly influenced by wave motions and are key to understanding issues such as beach erosion and protection, bottom morphology, water clarity, mine burial, surface wave energy budgets, and bottom friction experienced by mean currents. Our work is an effective means of developing and testing parameterizations for small-scale processes that must be considered in larger scale modeling efforts.

TRANSITIONS

Our work has taken a new direction through discussions with Tim Stanton (Naval Postgraduate School) based on results from measurements of the WBBL during SHOWEX. We are now emphasizing flow behavior over rough topography characteristic of that environment. The field data is input to our numerical experiments and output aids in interpreting the field observations to develop optimal models for estimating dissipation rates.

RELATED PROJECTS

1-Tim Stanton and Ed Thornton at the Naval Postgraduate School are making field measurements as a part of the ONR DRI on Shoaling Surface Waves.

2- Kraig Winters at the University of Washington has been instrumental in developing the model for flow over complex topography.

3-D.N. Slinn, Office of Naval Research, 321CD, Coastal Dynamics, Nonlinear Time Dependent Currents in the Surfzone. 1999-2002. Coupling of wave field and mean current interactions is the focus of this intermediate scale nearshore modeling study. Simple parameterizations for bottom boundary layer dissipation that are employed can be improved by insight gained from the WBBL study.

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PUBLICATIONS

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Moneris, S. S. and D. N. Slinn, 2000, Numerical simulation of wave energy dissipation in turbulent boundary layers, Part 1: Three-dimensional simulation, draft completed, to be submitted to J. Geophysical Res.

Moneris, S. S. and D. N. Slinn, 2000, Numerical simulation of wave energy dissipation in turbulent boundary layers, Part 2: One-dimensional eddy-viscosity models, draft completed, to be submitted to J. Geophysical Res.